New directions in VLQs searches

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Preliminary work [1712.XXXXX,T.Flacke, G. Cacciapaglia,N. Bizot]

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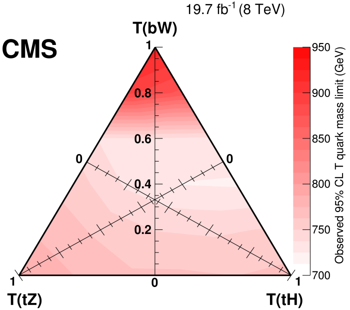
Current VLQs searches

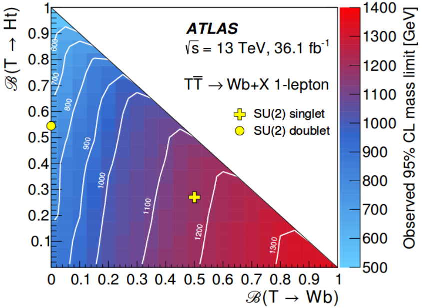
Currents searches focus on VLQs decays into SM particles and assume:

- $Br(T \to Zt, ht, W^+b) = 1$,
- $Br(X_{5/3} \to W^+t) = 1$,
- $Br(B \to Zb, hb, W^-t) = 1$
- $Br(Y_{-4/3} \to W^-b) = 1$

VLQs can be:

- pair produced (QCD) $\Rightarrow$ model-independent
- singly produced (EW) $\Rightarrow$ depends on mixing with SM quarks





Vector-like: left and right-handed chiralities have same quantum number such that mass term is allowed in opposition to SM chiral fermions

Composite Higgs models:

- Higgs emerges as pNGB (like QCD pions) $\Rightarrow$ Naturally light
- Simplest realisation: four-dimensional gauge theory of fermions (like QCD)

$\Rightarrow$ Non-minimal models [beyond $SO(5)/SO(4)$]

New channels in composite Higgs models (CHMs)

Generic prediction: presence of additional light states (pNGBs) involved in VLQs decays $\Rightarrow$ 4 promising decay modes

- EW-singlet mode: $T \to \eta t$ [η = EW pNGB like Higgs]
- $U(1)$-mode: $T \to a t$ [a = pNGB associated to non-anomalous $U(1)$]
- Coloured mode: $X_{5/3} \to \pi_6 \overline{b}$ [π_6 = Coloured pNGB]
- Charged mode: $X_{5/3} \to \phi^+ t$ [ϕ^+ = EW pNGB like Higgs]

$\Rightarrow$ Large branching ratios predicted: reduce experimental bound on M_{VLQs}
$\Rightarrow$ Well-defined theoretical framework: couplings predicted not added by hand

Strategy: Choose a model (underlying theory, top partner irreps)
look at benchmark scenarios (fix pre-Yukawa, VL masses)

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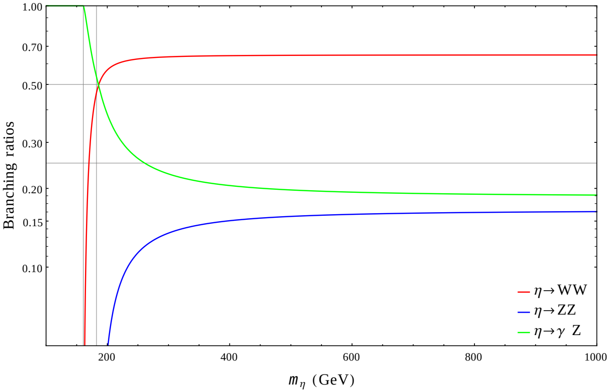
- Lightest VLQ T: pure EW singlet, no mixing with SM quarks

$\Rightarrow$ No single production

- No standard decays as T couples only to ηt

$\Rightarrow$ $Br(T \to \eta t) = 1$

EW singlet η decays into SM particles ($m_\eta \gtrsim 100$ GeV as same origin as Higgs boson)



- Anomalous couplings to SM gauge bosons [Cacciapaglia, Deandrea et al, 1502.04718]

$\Rightarrow$ $WW, \gamma Z, ZZ$ decays

$\Rightarrow$ No $\gamma\gamma$ coupling

- No decays into SM fermions

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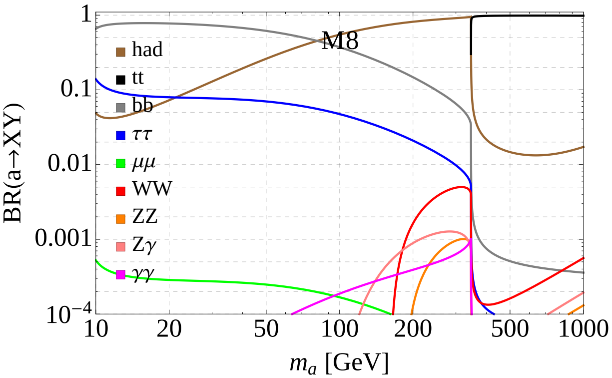
- Lightest VLQ T (mix singlet-doublet) mixes with SM top quark

$\Rightarrow$ Pair and single production relevant

- EW singlet a associated to non-anomalous $U(1)$-symmetry

[Spontaneously broken contrary to $U(1)_V$ in QCD $\to$ a is a pNGB]

$\Rightarrow$ can be very light (10 GeV $\lesssim m_a \lesssim 1$ TeV) as different origin compare to Higgs boson mass



- Anomalous decays into SM gauge bosons

$\Rightarrow$ $gg, WW, ZZ, Z\gamma, \gamma\gamma$

- Decays into all SM fermions

$\Rightarrow$ Couplings proportional to fermion masses (like Higgs)

$\Rightarrow$ Branching strongly depend on m_a

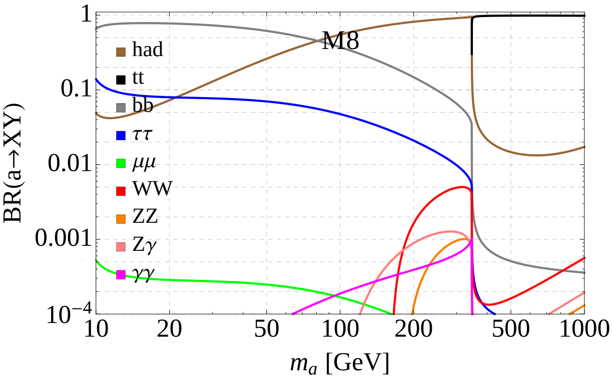
- Lightest VLQ T (mix singlet-doublet) mixes with SM top quark

$\Rightarrow$ Pair and single production relevant

- EW singlet a associated to non-anomalous $U(1)$-symmetry

[Spontaneously broken contrary to $U(1)_V$ in QCD $\to$ a is a pNGB]

$\Rightarrow$ can be very light ($10 \text{ GeV} \lesssim m_a \lesssim 1 \text{ TeV}$) as different origin compare to Higgs boson mass



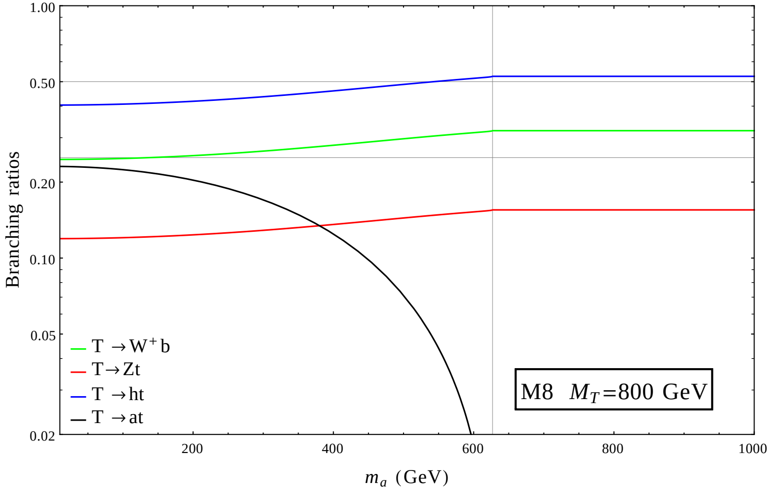
Low mass region:

- a decays mainly into $b\bar{b}$, $\tau\tau$ and hadrons

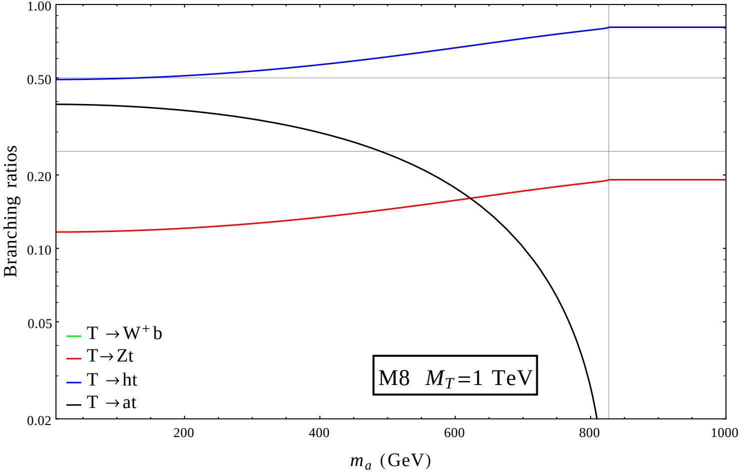
Hight mass region:

- Below $t\bar{t}$ threshold decay mainly into hadrons (also $b\bar{b}$ and $\tau\tau$)
- Above threshold a decays almost exclusively into $t\bar{t}$

- Standard channels + at-channel $\Rightarrow$ 4 dimensional parameter space (should extend 'triangle' plots)
- Below threshold $T \to at$ dominates in general



$T \to at$



- $T \to at$ depends on m_T
- Ratio between singlet and doublet components (mixing) of T also depends on m_T

$\Rightarrow$ Relevant to explore $Br(T \to ht, Wb, Zt) + Br(T \to at) = 1$

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- Lightest VLQ is $X_{5/3}$ is part of EW-doublet $(X_{5/3}\, T) \sim (3, 2, 7/6)$

$\Rightarrow$ Pair-produced from QCD

- Non-negligible $X_{5/3} \to \pi_6 \overline{b}$ branching ratio w.r.t standard $X_{5/3} \to W^+ t$

$\Rightarrow$ Two dimensional parameter space

π_6 decays

- pNGB sextet π_6 associated to spontaneously broken global symmetry of the coloured sector (required to form composite VLQs)

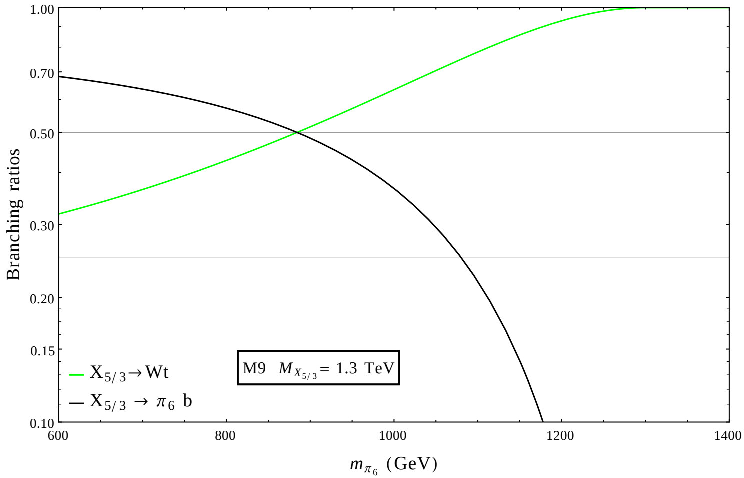
$\Rightarrow$ Direct searches lead to $m_{\pi_6} \gtrsim 600 - 700$ GeV [Cacciapaglia, Deandrea, Flacke et al, 1507.02283]

- Decay only into tops $\pi_6 \to tt$ $\pi_6 \sim (6, 1, 4/3)$

$\Rightarrow$ No decays into SM gauge bosons (hypercharge)

$\Rightarrow$ No decays into light fermions (partial compositeness vs bilinear coupling)

Relevant to explore $Br(W^+ t) + Br(\pi_6 \bar{b}) = 1$



Summary

- Simplest realisation of composite Higgs model is a 4D gauge theory of fermions that condenses at low energy
$\Rightarrow$ Higgs naturally light as pNGB
$\Rightarrow$ Additional EW pNGB $\eta, \phi^+, \cdots$ (depending on the underlying model)

- EWSB requires partial compositeness for top quark
$\Rightarrow$ Coloured pNGBs $\pi_6, \cdots$ $\Rightarrow$ Additional $U(1)$-singlet a

Final states

- EW-singlet mode: $T \to \eta t, \quad \eta \to WW, \gamma Z, ZZ$
pair-production only , $m_\eta \gtrsim 100$ GeV
- U(1)-mode: $T \to at, \quad a \to t\bar{t}$ (hight mass), hadrons, $b\bar{b}, \tau\tau$ (low mass)
pair+single production, m_a could be very light ~ 10 GeV
- Coloured mode: $X_{5/3} \to \pi_6 \bar{b}, \quad \pi_6 \to tt$
- Charged mode: $X_{5/3} \to \phi^+ t, \quad \phi^+ \to W^+\gamma, W^+Z$

Model-dependant scenarios
$\Rightarrow$ Typical behaviour only (benchmarks scenarios from theory side)
$\Rightarrow$ Variations are possible (depending on the model, underlying gauge theory)

Final states

- EW-singlet mode: $T \to \eta t$

Pair production: $pp \to T\overline{T} \to (\eta t)(\eta \bar{t})$, $\eta \to WW, \gamma Z, ZZ$

- U(1)-mode: $T \to at$

Pair production: $pp \to T\overline{T} \to (at)(a\bar{t})$ or $(at)(Z\bar{t}, h\bar{t}, W^- \bar{b})$

Single production: $pp \to T \to at$

- Coloured mode: $X_{5/3} \to \pi_6 \bar{b}$

Pair production: $pp \to X_{5/3}\overline{X}_{5/3} \to (\pi_6 \bar{b})(\pi_6^c b) \to (tt\bar{b})(\bar{t}\bar{t}b)$

$pp \to X_{5/3}\overline{X}_{5/3} \to (W^+ t)(\pi_6^c b) \to (W^+ t)(\bar{t}\bar{t}b)$

- Charged mode: $X_{5/3} \to \phi^+ t$

Pair production: $pp \to X_{5/3}\overline{X}_{5/3} \to (\phi^+ t)(\phi^- \bar{t}) \to (W^+ \gamma t)(W^- \gamma \bar{t})$

$pp \to X_{5/3}\overline{X}_{5/3} \to (W^+ t)(\phi^- \bar{t}) \to (W^+ t)(W^- \gamma \bar{t})$

- Lightest VLQ is $X_{5/3}$ is part of EW-doublet $(X_{5/3}\,T) \sim (3,2,7/6)$

$\Rightarrow$ Pair-produced from QCD

- Non-negligible $X_{5/3} \to \phi^+ t$ branching ratio w.r.t standard $X_{5/3} \to W^+ t$

$\Rightarrow$ Two dimensional parameter space (coloured pNGB can easily be heavier than VLQs)

ϕ^+ decays

- pNGB ϕ^+ is an EW triplet (same origin as the Higgs boson)

$$\Phi_+ = \left(\phi^{++} \quad \phi^+ \quad \phi^0\right)^T \sim (1,3,1)\ , \qquad \Phi_+ = \left(\phi^+ \quad \phi^0 \quad \phi^-\right)^T \sim (1,3,0)\ ,$$

- Anomalous couplings: $\phi^+ \to W^+\gamma$ and $\phi^+ \to W^+ Z$ from $\Phi_0 W^{\mu\nu} \tilde{B}_{\mu\nu}$

$\Rightarrow$ $W^+\gamma$ channel dominates

- Decays into SM fermions: $\phi^+ \to t\bar{b}$ from $\Phi_+^a (\overline{q}_L \tilde{H})^a b_R$ or $\Phi_0^a (\overline{q}_L H)^a b_R$

(also decays into light quarks and leptons) $\Rightarrow$ Supressed by v/f

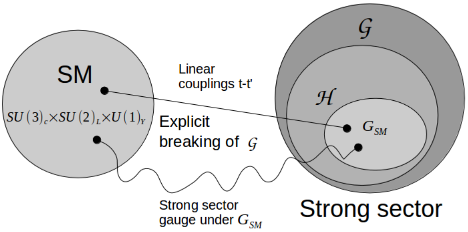
- $\Gamma_{\phi^+ W^+ V} \sim m_{\phi^+}^3$ while $\Gamma_{W^+ tb} \sim m_{\phi^+}$ $\Rightarrow$ decays into spin 1 is dominant

- New strong dynamics condensates at scale Λ and spontaneously breaks a global symmetry G into H
$\Rightarrow$ Higgs is naturally light as a pNGB leaving in the coset G/H (like QCD pions)

- Potential and mass for the Higgs generated by explicit breaking terms

Gauging of SM symmetry

SM gauge symmetry embedded inside unbroken group H
$\Rightarrow$ Can not destabilise Higgs potential and induce EWSB ($\Delta M_H^2 > 0$)
$\Rightarrow$ Another explicit breaking source is required



Partial compositeness

- Linear couplings between top and top partners
$\Rightarrow$ induce EWSB and top mass

- Top quark heaviest SM particle
$\Rightarrow$ Largest interaction with strong sector

- Bilinear couplings for other SM fermions

Structure of the underlying theory

Barring extra space-time dimensions:
Simplest, well-understood, explicit realization provided by 4D gauge theory of fermions that confines at the multi-TeV scale Λ

$\Rightarrow$ No fundamental scalar reintroducing hierarchy problem at higher scale

Fundamental fermions

pNGB Higgs + top partners (PC)

$\Rightarrow$ Two species of fundamental fermions (novel feature compare to QCD)

- EW sector (Higgs sector): fermions ψ
  $\Rightarrow$ Spontaneous symetry breaking should deliver at least 4 pNGBs associated to Higgs doublet: $H \sim (\psi\psi)$
- Coloured sector: fermions X
  $\Rightarrow$ Some trilinear bound states $(\psi\psi X)$ or $(\psi X X)$ should have same quantum numbers as SM top quark multiplets
  $\Rightarrow$ Spontaneous breaking delivers additional coloured pNGBs $(XX) \sim \pi^c$

Minimal fermionic UV completion

First example provided by:

EW sector $SU(4)/Sp(4) \cong SO(6)/SO(5)$

- $SU(4)/Sp(4) \Rightarrow$ only 15-10 $= 5$ NGBs: Higgs doublet + singlet η
- 4 Weyl fermions $\psi \Rightarrow SU(4)$ global symmetry
- $Sp(4) \Rightarrow \psi$ belong to a pseudo-real hypercolour representation:
  the fundamental of $Sp(2N)$ [Barnard et al, '13]

Coloured sector $SU(6)/SO(6)$

- $SU(6)/SO(6) \Rightarrow$ 35-15 $= 20$ coloured NGBs: π_8, π_6 and π_6^c
- 6 Weyl fermions $\chi \Rightarrow SU(6)$ global symmetry
- $SO(6) \Rightarrow \chi$ belong to a real hypercolour representation:
  2-index antisymmetric of $Sp(2N)$

$G_{\rm HC}$	ψ	χ	Restrictions	$-q_\chi/q_\psi$	Y_χ	Non Conformal	Model Name
	Real	Real	SU(5)/SO(5) × SU(6)/SO(6)				
$SO(N_{\rm HC})$	$5\times\mathbf{S}_2$	$6\times\mathbf{F}$	$N_{\rm HC}\geq 55$	$\frac{5(N_{\rm HC}+2)}{6}$	1/3	/	
$SO(N_{\rm HC})$	$5\times\mathbf{Ad}$	$6\times\mathbf{F}$	$N_{\rm HC}\geq 15$	$\frac{5(N_{\rm HC}-2)}{6}$	1/3	/	
$SO(N_{\rm HC})$	$5\times\mathbf{F}$	$6\times\mathbf{Spin}$	$N_{\rm HC}=7,9$	$\frac{5}{6},\frac{5}{12}$	1/3	$N_{\rm HC}=7,9$	M1, M2
$SO(N_{\rm HC})$	$5\times\mathbf{Spin}$	$6\times\mathbf{F}$	$N_{\rm HC}=7,9$	$\frac{5}{6},\frac{5}{3}$	2/3	$N_{\rm HC}=7,9$	M3, M4
	Real	Pseudo-Real	SU(5)/SO(5) × SU(6)/Sp(6)				
$Sp(2N_{\rm HC})$	$5\times\mathbf{Ad}$	$6\times\mathbf{F}$	$2N_{\rm HC}\geq 12$	$\frac{5(N_{\rm HC}+1)}{3}$	1/3	/	
$Sp(2N_{\rm HC})$	$5\times\mathbf{A}_2$	$6\times\mathbf{F}$	$2N_{\rm HC}\geq 4$	$\frac{5(N_{\rm HC}-1)}{3}$	1/3	$2N_{\rm HC}=4$	M5
$SO(N_{\rm HC})$	$5\times\mathbf{F}$	$6\times\mathbf{Spin}$	$N_{\rm HC}=11,13$	$\frac{5}{24},\frac{5}{48}$	1/3	/	
	Real	Complex	SU(5)/SO(5) × SU(3)²/SU(3)				
$SU(N_{\rm HC})$	$5\times\mathbf{A}_2$	$3\times(\mathbf{F},\overline{\mathbf{F}})$	$N_{\rm HC}=4$	$\frac{5}{3}$	1/3	$N_{\rm HC}=4$	M6
$SO(N_{\rm HC})$	$5\times\mathbf{F}$	$3\times(\mathbf{Spin},\overline{\mathbf{Spin}})$	$N_{\rm HC}=10,14$	$\frac{5}{12},\frac{5}{48}$	1/3	$N_{\rm HC}=10$	M7
	Pseudo-Real	Real	SU(4)/Sp(4) × SU(6)/SO(6)				
$Sp(2N_{\rm HC})$	$4\times\mathbf{F}$	$6\times\mathbf{A}_2$	$2N_{\rm HC}\leq 36$	$\frac{1}{3(N_{\rm HC}-1)}$	2/3	$2N_{\rm HC}=4$	M8
$SO(N_{\rm HC})$	$4\times\mathbf{Spin}$	$6\times\mathbf{F}$	$N_{\rm HC}=11,13$	$\frac{8}{3},\frac{16}{3}$	2/3	$N_{\rm HC}=11$	M9
	Complex	Real	SU(4)²/SU(4) × SU(6)/SO(6)				
$SO(N_{\rm HC})$	$4\times(\mathbf{Spin},\overline{\mathbf{Spin}})$	$6\times\mathbf{F}$	$N_{\rm HC}=10$	$\frac{8}{3}$	2/3	$N_{\rm HC}=10$	M10
$SU(N_{\rm HC})$	$4\times(\mathbf{F},\overline{\mathbf{F}})$	$6\times\mathbf{A}_2$	$N_{\rm HC}=4$	$\frac{2}{3}$	2/3	$N_{\rm HC}=4$	M11
	Complex	Complex	SU(4)²/SU(4) × SU(3)²/SU(3)				
$SU(N_{\rm HC})$	$4\times(\mathbf{F},\overline{\mathbf{F}})$	$3\times(\mathbf{A}_2,\overline{\mathbf{A}}_2)$	$N_{\rm HC}\geq 5$	$\frac{4}{3(N_{\rm HC}-2)}$	2/3	$N_{\rm HC}=5$	M12
$SU(N_{\rm HC})$	$4\times(\mathbf{F},\overline{\mathbf{F}})$	$3\times(\mathbf{S}_2,\overline{\mathbf{S}}_2)$	$N_{\rm HC}\geq 5$	$\frac{4}{3(N_{\rm HC}+2)}$	2/3	/	
$SU(N_{\rm HC})$	$4\times(\mathbf{A}_2,\overline{\mathbf{A}}_2)$	$3\times(\mathbf{F},\overline{\mathbf{F}})$	$N_{\rm HC}=5$	4	2/3	/	

Several other possibilities exist:

- EW and coloured cosets changed
- Fundamental fermions are not the same

[Belyaev et al, 1610.06591]

Additional pNGBs

In addition to the Higgs doublet, additional EW pNGBs are present

EW sector

Smallest cosets constructed from pseudoreal, real or complex representations:

- $SU(4)/Sp(4)$: $5_{Sp(4)} \equiv \mathbf{A}_2 = 2_{\pm 1/2} + 1_0$ $\quad (H, \eta)$
- $SU(5)/SO(5)$: $14_{SO(5)} \equiv \mathbf{S}_2 = 3_{\pm 1} + 3_0 + 2_{\pm 1/2} + 1_0$ $\quad (\Phi_\pm, \Phi_0, H, \eta)$
- $SU(4) \times SU(4)/SU(4)$: $15_{SU(4)} \equiv \mathbf{Ad} = 3_0 + 2_{\pm 1/2} + 2_{\pm 1/2} + 1_{\pm 1} + 1_0 + 1_0$ $\quad (\Phi_0, H_1, H_2, N_\pm, N_0, \eta)$

[Ma, Cacciapaglia, 1508.0714]

$\Rightarrow$ Always SM-like singlet η $\quad \Rightarrow$ Sometimes triplets or second Higgs doublet

Coloured sector

- $SU(6)/SO(6) \supset SU(3)_c$: $20'_{SO(6)} \equiv \mathbf{A}_2 = 8_0 + 6_{4/3} + \overline{6}_{-4/3}$ $\quad (\pi_8, \pi_6, \pi_6^c)$
- $SU(6)/Sp(6) \supset SU(3)_c$: $14_{Sp(6)} \equiv \mathbf{S}_2 = 8_0 + 3_{-4/3} + \overline{3}_{4/3}$ $\quad (\pi_8, \pi_3, \pi_3^c)$
- $SU(3) \times SU(3)/SU(3)_c$: $8_{SU(3)} \equiv \mathbf{Ad} = 8_0$ $\quad (\pi_8)$

$\Rightarrow$ Always a coloured octet π_8 $\quad \Rightarrow$ Sometimes coloured triplets or sextets

[Cacciapaglia et al, 1507.02283, 1610.06591]

Anomalous couplings

pNGBs may couple to gauge bosons through anomalies ($\pi^0 \to \gamma\gamma$ in QCD)

$$\mathcal{L}^{WZW} = -\frac{g_{\mathcal{W}}^2}{64\pi^2}\frac{d_{HC}}{F_G}\epsilon_{\mu\nu\rho\sigma}\mathcal{W}^{\mu\nu}\mathcal{W}^{\rho\sigma}\sum_{\hat{A}} d^{WW\hat{A}}G^{\hat{A}} + \cdots$$

$$d^{WW\hat{A}} = 2Tr(\{T^W, T^W\}T^{\hat{A}})$$

$\Rightarrow$ Non-zero couplings depend on the coset (global symmetries)
$\Rightarrow$ Stength depends on the underlying theory (fundamental fermions irreps)

EW pNGBs

- No anomalous couplings for the Higgs boson
- $\underline{SU(4)/Sp(4)}$ ηZZ, $\eta\gamma Z$, ηWW
- $\underline{SU(5)/SO(5)}$ $\eta\gamma\gamma$ ηZZ, $\eta\gamma Z$, ηWW, triplet anomalous couplings, $\cdots$

Coloured pNGBs

- π_8 decays in gg, γg or Zg via anomaly (and top triangle loop)

In general PC implies decays of pNGBs into tops ($\eta \to t\bar{t}$, $\pi_6 \to tt$, $\cdots$)

- EW ψ fermions: anomalous $U(1)_\psi$
- Coloured X fermions: anomalous $U(1)_X$

$\Rightarrow$ Always a non-anomalous combination w.r.t hypercolour

$$q_\psi N_\psi T(\psi) + q_X N_X T(X) = 0$$

$\Rightarrow$ One additional light pNGB a

$\Rightarrow$ Other pseudoscalar η' receive mass from anomaly (instanton effects), could be light as no way to estimate anomaly coefficient

Anomalous couplings

- η_ψ to $SU(2)_L \times U(1)_Y$ gauge bosons ($\eta_\psi WW, BB$) [Cai et al, 1512.04508]
- η_X to $SU(3)_c \times U(1)_Y$ gauge bosons ($\eta_X gg, BB$)

$\eta_\psi - \eta_X$ mixing:

$$\begin{cases} a = \cos\phi\ \eta_\psi + \sin\phi\ \eta_X \\ \eta' = -\sin\phi\ \eta_\psi + \cos\phi\ \eta_X \end{cases} \qquad \tan\phi = \frac{f_X q_X}{f_\psi q_\psi}$$

$\Rightarrow$ a produced by gluon fusion (contrary to EW pNGBs)

$\Rightarrow$ a decays to dibosons ($gg, WW, ZZ, Z\gamma, \gamma\gamma$) and $t\bar{t}$ thanks to PC

[Belyaev et al, 1610.06591]

Trilinear baryons $(\psi\psi X)$ in the $6_{SU(4)} = (5+1)_{Sp(4)} = (2,2)+(1,1)+(1,1)$
$= 2_{7/6} + 2_{1/6} + 1_{2/3} + 1_{2/3}$

In the $\{t, T, X_{2/3}, \tilde{T}_1, \tilde{T}_5\}$ basis:

$$M_{top} = \begin{pmatrix} 0 & -y_{5L} f \cos^2\frac{\theta}{2} & y_{5L} f \sin^2\frac{\theta}{2} & \frac{y_{1L} f}{\sqrt{2}} s_\theta & 0 \\ \frac{y_{5R} f}{\sqrt{2}} s_\theta & M_5 & 0 & 0 & 0 \\ \frac{y_{5R} f}{\sqrt{2}} s_\theta & 0 & M_5 & 0 & 0 \\ -y_{1R} f c_\theta & 0 & 0 & M_1 & 0 \\ 0 & 0 & 0 & 0 & M_5 \end{pmatrix}$$

$\Rightarrow$ $\tilde{T}_5$ does not mix

$\tilde{T}_5$ and $X_{5/3}$ decays

- η couplings only involve $\tilde{T}_5$: $\mathcal{L}_\eta = -\frac{y_{5R} f}{\sqrt{2}} i t_R^c \tilde{T}_5 c_\theta \frac{\eta}{f} + \frac{y_{5L} f}{\sqrt{2}} i \tilde{T}_5 t_L s_\theta \frac{\eta}{f}$

$\Rightarrow$ $\tilde{T}_5$ only decays into ηt (or $\eta t'$)

- In general the lightest states are $m_{\tilde{T}_5} = m_{X_{5/3}} \equiv M_5$

$\Rightarrow$ $Br(\tilde{T}_5 \to \eta t) = 1 \to$ Non-standard channel